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EXPERIMENTAL STUDY OF LIGHTWEIGHT TRACKED VEHICLE PERFORMANCE ON DRY GRANULAR MATERIALS

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Abstract

This paper presents an experimental study of the performance of a single track device driving on dry, granular soils. A single-track test rig is used to empirically investigate track motion under controlled track slip and loading conditions on three natural dry granular materials:a dry sandy material with 100 um average grain size, a dry sandy material with 400 um average grain size, and a coarse gravel with 1 cm average particle size. Test conditions can be designed to replicate typical field scenarios for lightweight robots, while key operational parameters such as drawbar force, torque, and sinkage are measured. This test rig enables imposition of velocities, or application of loads, to interchangeable running gears within a confined soil bin of dimensions 1.5 m long, 0.7 m wide, and 0.4 m deep. The tested single track device has an effective contact area measuring approximately 25 cm x 10 cm and it is tested under three vertical loads 125 N, 155 N, and 190 N. Slip is varied within -50% and +50% during travel over the three soils. The track utilizes a flexible rubber belt equipped with 0.5 cm tall grousers. Experimental measurements are compared against well-established semi-empirical models, to assess the predictive accuracy of these models .

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1. Introduction

When compared to wheels, tracks generally guarantee improved mobility capabilities [17] at the cost of increased complexity in the running gear mechanism. Therefore, depending on mobility and design requirements, tracks are an interesting alternative to wheels. This paper presents an experimental study of the performance of a single track device traveling on dry, granular soils. Although in recent years several lightweight robotic systems have adopted tracks mechanism as running gears, no experimental study of a single track device moving on granular material exists to date. Moreover, the vast majority of previous studies has focused on large, heavyweight vehicles, while this current work studies lightweight vehicles (lacking a standardized classification, in this paper we arbitrarily define lightweight vehicles as having average ground pressure below 20 kPa. Many space rovers and robotic ground vehicles fall within this classification).

Some of the relevant literature includes the work by Dhir and Sankar [2] who presented various modeling strategies for track dynamic simulations. They demonstrated the influence of various track models on the ride dynamic prediction of tracked vehicle. Their analysis focused on large military vehicles and they showed that the track dynamics can significantly influence the entire vehicle dynamics. Dwyer et al. [3] investigated the performance of a tracked agricultural tractor and found that the length of the ground contact area is the most important factor affecting tractive performance, while track tension does not play a primary role on cohesive soils. The work by Watanabe et al. [14] is one of the few examples where relatively small tracked devices were tested. The authors present a model for characterization of dynamic soil-track interaction on dry sand, and conduct experiments using independent suspension, fixed suspension, and skid-type suspension tracked vehicles (50.5 kg mass, 0.41 m x 0.29 m ground contact area). Track shoes were equipped with sensors for normal pressure, shear stress, and tension measurement, but unfortunately the paper does not present extensive data for different slip levels and loading conditions. Negrut et al. [7] showed how discrete element method could be employed to predict mobility of lightweight vehicles.

The most recognized work is probably the work of Wong, who has presented semi-empirical methods for tracked vehicle mobility prediction based on Bekker terramechanics theories [16, 15]. These reduced order models, primarily developed and validated for heavy military vehicles, have been utilized, modified, and extended in several studies [5, 8, 13, 10, 11].

This research explores the mobility performance of a single track traveling on three different granular materials: a dry sandy material with 100 um average grain size, a dry sandy material with 400 um average grain size, and a coarse gravel with 1 cm average particle size. Tests are conducted under low average ground pressure in order to reproduce the conditions of typical lightweight robotic systems. Measurements of drawbar pull force and sinkage are compared against two semi-empirical track models: the basic Wong model (BWM) and the advanced Wong model (AWM). The BWM assumes uniform ground pressure distribution, while the AWM treats the track as a flexible belt, thus producing much richer outputs. Results obtained with the AWM are more accurate, but both methods lack the capability to properly predict slip-sinkage dependency.

The paper is organized as follows: Experimental Setup presents the terramechanics rig, the track device, and the granular materials utilized for this work. Experimental Data Collection and Discussion section is articulated in 3 subsections: first we present an overview of track performance as function of vertical load on the three sands; then we show the influence of terrain type on track mobility; finally we introduce two modeling approaches and we compare model predictions with experimental data.

2. Experimental Setup

2.1. Terramechanics single track test rig

The Robotic Mobility Group at MIT has designed and fabricated a multi-purpose terramechanics rig based on the standard design described by Iagnemma [4]. The test bed is pictured in Figure 1 and it is composed of a Lexan soil bin surrounded by an aluminum frame where all the moving parts, actuators and sensors are attached. A carriage slides on two low-friction rails to allow longitudinal translation while the track, attached to the carriage, is able to rotate at a desired angular velocity. The track mount is also able to freely translate in the vertical direction. This typical setup allows control of slip and vertical load by modifying the translational velocity of the carriage, angular velocity of the drive sprocket of the track, and applied load. Horizontal carriage displacement is controlled through a toothed belt actuated by a 90 W Maxon DC motor, while the track is driven by a 150 W Maxon DC motor. The motors are controlled through two identical Maxon ADS 50/10 4-Q-DC servo-amplifiers. The carriage horizontal displacement is monitored with a Micro Epsilon WPS-1250-MK46 draw wire encoder while track vertical displacement (i.e., sinkage) is measured with a Turck A50 draw wire encoder.

A 6-axis force torque ATI Omega 85 transducer is mounted between the track mount and the carriage in order to measure vertical load and traction generated

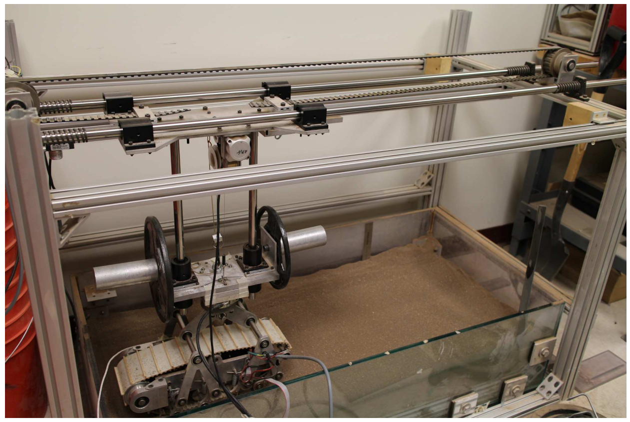


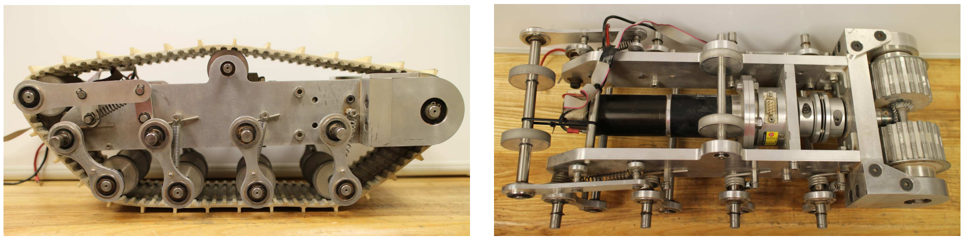
Figure 1: The terramechanics rig at MIT.

by the track. Control and measurement signals are handled by a NI PCIe-6363 card through Labview software. The rig is capable of approximately 1 meter of horizontal displacement at a maximum velocity of approximately 120 mm/s. The bin width is 0.6 meters while the soil depth is 0.16 meters. Considering the track sizes and vertical loads under study, these physical dimensions are sufficient for eliminating boundary effects.

Moreover, the same test bed, with some adaptations, can be used to perform soil penetration tests.

2.2. Track design

The device utilized for this research is a unique platform designed to evaluate the tractive performance of small single tracks. An aluminum frame encloses the drive-train system while the suspension system is mounted externally. The drive-train includes a motor assembly (encoder, motor, and gear head), a flange-to-flange Futek TFF500 torque sensor, a flexible coupling, a one-to-one bevel gear transmission, and two toothed pulleys as shown in Figure 2(b). The suspension system is composed of four roadwheels connected to trailing arm-type suspensions and a tensioner assembly as presented in Figure 2(a). The running-gear is a 92 shore A durometer toothed belt produced by BrecoFlex: the belt width is 100 mm while the length of the contact area is approximately 250 mm. The lugs are straight, measure 5.5 mm in height, and are separated by 33 mm. These dimensions were chosen in order to guarantee sufficient track-terrain engagement.



(a) (b)

Figure 2: (a) The single track device has four roadwheels connected to trailing arm suspensions. A tensioner guarantees proper tensioning of the belt element. (b) The drivetrain is enclosed inside the main frame and includes a motor, a flange-to-flange torque sensor, a flexible coupling, one-to-one bevel gear transmission and two toothed pulleys that act like driving sprockets.

2.3. Terrain simulants

For the experiments described in this paper, three granular materials were used: the Mojave Martian Simulant (MMS), the Quikrete Medium Sand 1962 (MS), and the Quikrete All Purpose Gravel 1151 (GV) (see Figure 3). MMS is a mixture of finely crushed and sorted granular basalt intended to mimic, both at chemical and mechanical levels, the Mars soil characteristics [9]. MMS particle size distribution spans from micron to millimeter scale, with 80% of particles above the 10 micron threshold. The MS and GV are commercially available products: MS is a silica sand with predominant size in the 0.3 - 0.8 mm range while GV has approximate maximum size of 10 mm.

For the MMS and MS, direct shear tests were conducted. The GV, however, could not be tested in the direct shear apparatus because of its large grain size,

(a) (b) (c)

Figure 3: (a) Mojave Martian Simulant (MMS), (b) Quikrete Medium Sand 1962 (MS), (c) Quikrete All Purpose Gravel 1151 (GV).

Table 1: Mojave Martian Simulant (MMS) and Quikrete Medium Sand (MS) properties were measured through a series of plate penetration tests and direct shear tests. It should be noted that the shear modulus is very small [12]. GV could not be tested in the direct shear box due to its large particle size, and therefore the angle of internal friction was estimated from the angle of repose of the material.

Material	n [-]	k_c [kN/m^{n+1}]	k_ϕ [kN/m^{n+2}]	c [Pa]	ϕ [deg]	k [m]
MMS	1.4	846	6708	600	35	0.0006
MS	1.0	-20	3130	1500	34	0.0006
GV	n/a	n/a	n/a	n/a	30	n/a

and thus the angle of internal friction for this material was deduced from its angle of repose. For the MMS and MS, also plate penetration tests were conducted and therefore Bekker parameters were obtained. Available soil properties are presented in Table 1. It should be noted that the shear modulus for the MMS and MS is very small. Typical literature values range between 0.01 and 0.03 m, however, as was presented in [12], correct calculation of shear modulus leads to a significantly smaller value of k.

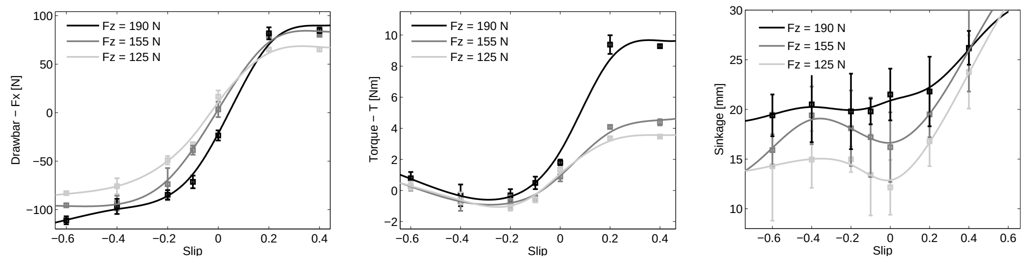
3. Experimental Data Collection and Discussion

Three vertical loads have been investigated, 125 N, 155 N, and 190 N, while 7 slip levels were selected: -50%, -30%, -10%, 0%, +10%, +30%, +50%. During experiments, the longitudinal velocity of the track was held constant at 50 mm/s, while the angular velocity of the track was varied, for each slip level, according to the following equation:

$$i = 1 - \frac{v}{\omega r} \tag{1}$$

where v is the track longitudinal velocity, r is the driving pulley radius, and ω is the pulley angular velocity.

Note that the same definition of slip was used for positive and negative slip tests. Each test was repeated 5 times, and the data presented here were obtained as the average of all the trials. The experimental results for drawbar, torque, and sinkage for all the materials will be presented in the following subsections.



(a) (b) (c)

Figure 4: (a) Drawbar, (b) torque, and (c) sinkage measurements on the MMS. The boxplot represents the standard deviation for the data point. The continuous line is a fit of the data points to highlight the trend.

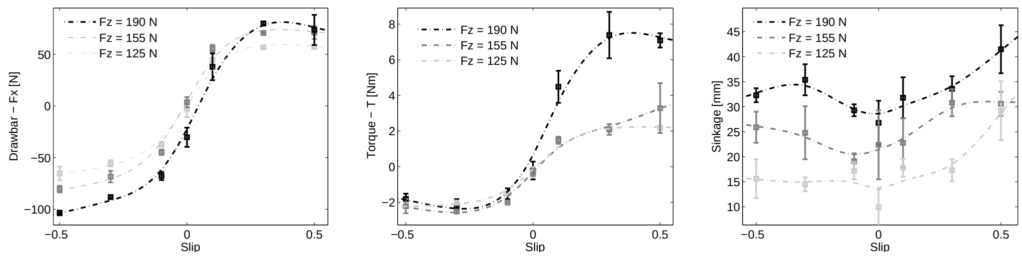
3.1. Influence of vertical load on track performance

Figures 4, 5, and 6 present drawbar, torque, and sinkage for the MMS, the MS, and the GV terrain at three vertical loads: 125 N, 155 N, and 190 N. For MMS, drawbar force increases, in absolute value, for larger vertical loads (Figure 4(a)). As expected, drawbar force is larger for negative slip because compaction resistance due to sinkage provides additional braking force. The plots of drawbar force vs. slip show curves that are shifted toward positive slip for larger vertical loads.

This is a consequence of the static sinkage which increases the compaction resistance thus limiting traction for larger vertical loads. Drawbar increases significantly between F_z = 125 N and F_z = 155 N and only marginally between F_z = 155 N and F_z = 190 N. This suggests that the trade-off between shearing force and compaction resistance reaches a limit, for this configuration, around F_z = 155 N.

The plot of torque vs. slip, presented in Figure 4(b), shows how inefficient the motion becomes for F_z = 190 N (at positive slip). In order to obtain essentially the same drawbar twice as much torque is requested. For negative slip, compaction resistance dominates the braking force generation (i.e., drawbar for negative slip) and therefore torque stays low.

Sinkage, presented in Figure 4(c), shows that larger vertical loads induce larger sinkage as expected. For negative slip, sinkage does not grow with slip, this is because flow transport phenomena are more influential at positive slip than at negative slip (i.e., for positive slip the belt literally digs into the terrain while for negative slip it acts mostly as a plough). It should be noted that sinkage measurements show larger variability than drawbar and torque measurements. The draw-wire encoder used to measure sinkage is an accurate device, however errors are intro-



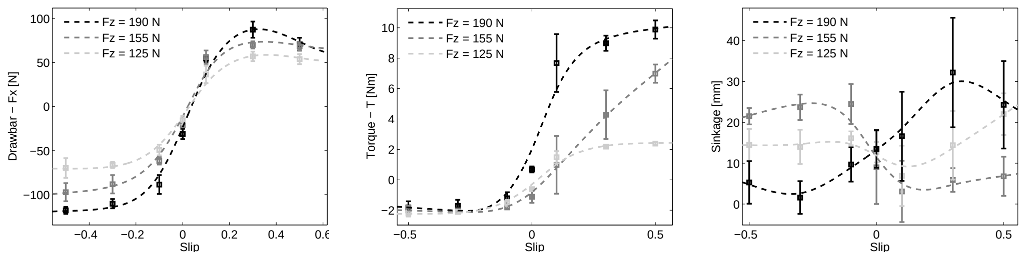
(a) (b) (c)

Figure 5: (a) Drawbar, (b) torque, and (c) sinkage measurements on the MS material. The boxplot represents the standard deviation for the data point. The continuous line is a fit of the data points to highlight the trend.

duced by three factors. First, sensor does not provide absolute readings and the soil height is not constant from test to test. Therefore, zero terrain elevation is estimated from vertical load readings and this process introduces measurements error. Moreover, although terrain is prepared carefully from test to test, the surface profile can present uneven regions. Finally, the track suspension sag variation may slightly affect sinkage readings.

The results obtained on the MS material are presented in Figure 5. Drawbar, torque, and sinkage behavior are similar to what was observed on the MMS terrain. Also, for the MS material, when vertical load is increased above F_z = 155 N, the traction efficiency diminishes drastically (i.e., torque doubles from F_z = 155 N to F_z = 190 N while drawbar increases modestly).

Track performance for the GV material are presented in Figure 6. Drawbar and torque exhibit similar behaviour to what was observed on MMS and MS. Drawbar shows a more dominant peak for 30% slip. For MS and MMS, torque at F_z = 125 N and F_z = 155 N are generally close for positive slip. However, for GV, torque shows larger sensitivity to vertical load (at least for positive slip). These evidences indicate that the interaction mechanism is closer to a classic friction interaction phenomenon (i.e., where friction forces are proportional to vertical load). Sinkage measurements for negative slip present a counter-intuitive behaviour: sinkage decreases for larger vertical loads. This could be interpreted by assuming that, for larger vertical loads, the gravel particles tend to interlock, thus not shearing under the track.

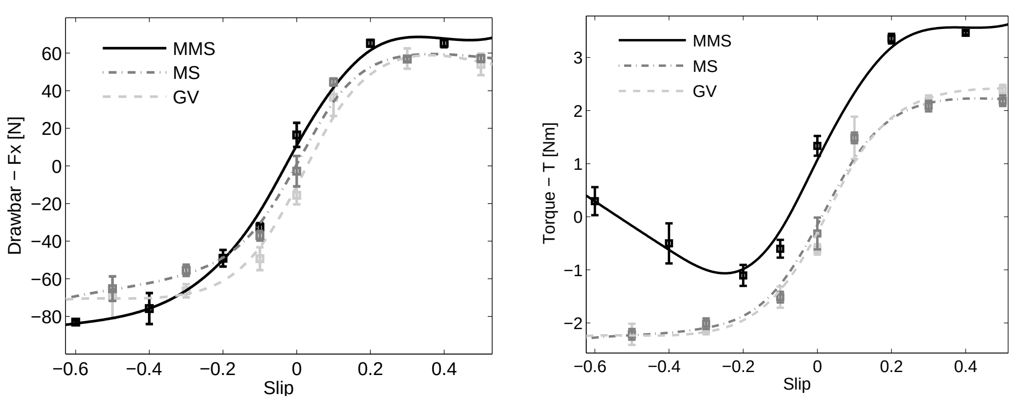


(a) (b) (c)

Figure 6: (a) Drawbar, (b) torque, and (c) sinkage measurements on the GV material. The boxplot represents the standard deviation for the data point. The continuous line is a fit of the data points to highlight the trend.

3.2. Influence of terrain on track performance

Although the three terrains under investigation present drastically different grain size distributions, the track performance is not markedly influenced by the simulant type. Figure 7(a) presents drawbar pull force for the three terrains for F_z = 125 N. Curves do not perfectly overlap but the behaviour between different materials is very close. Torque, on the other hand, shows that the MMS tends to require more torque than the other two terrains (see Figure 7(b)). This suggests that motion is less efficient on MMS as compared to MS or GV. The behavior is similar for other vertical loads.



(a) (b)

Figure 7: (a) Drawbar and (b) torque for all three materials under F_z = 125 N.

3.3. Modeling

As highlighted in the introduction, several track models have been developed in the past decades. Many of them are based on the semi-empirical approach proposed by Wong and derived from Bekker terramechanics theories. Here we will present the foundations of the Wong track model, and discuss its effectiveness for lightweight track modeling.

Assuming even load distribution under the track, it is possible to calculate the average ground pressure as:

$$p = \frac{F_z}{t_l t_w} \tag{2}$$

where F_z is the vertical load and t_l and t_w are the track length and width respectively. From the Bekker pressure-sinkage equation it is possible to derive the sinkage as:

$$z = \left(\frac{p}{\frac{k_c}{t_w} + k_\phi} \right)^{\frac{1}{n}} \tag{3}$$

where k_c, k_ϕ, and n, are Bekker pressure-sinkage parameters. Combining Janosi-Hanamoto equation and Mohr-Coulomb principle it is possible to calculate the thrust as:

$$T = t_w \int_0^{t_l} (c + p \tan\phi) \left(1 - \exp^{\frac{-ix}{k}}\right) dx \tag{4}$$

where c is cohesion, ϕ is the soil angle of internal friction, i is slip, and k is the shearing modulus. The compaction resistance can be calculated as the work needed to deform the terrain under the track as:

$$R_c = t_w \left(\frac{k_c}{t_w} + k_\phi \right) \left(\frac{z^{n+1}}{n+1} \right) \tag{5}$$

Therefore drawbar pull (i.e., net traction force), is obtained as:

$$F_x = T - R_c \tag{6}$$

This basic model can be used to facilitate comparison between vehicle design candidates and to assess the mobility of existing vehicles under specific scenarios. For instance the maximum thrust that a vehicle can develop can be calculated as:

$$F_{max} = A\tau = Ac + F_z \tan\phi \tag{7}$$

where A is the contact area and τ is the shear stress limit derived from the Mohr Coulomb criterion. For dry granular materials, cohesion is small, and traction is primarily dependent on normal load and angle of internal friction. Considering that MMS, MS, and GV have similar angle of internal friction, this explains why the performance of the track on these three media is similar.

The basic Wong model (BWM) can predict drawbar for different slip levels but it cannot predict sinkage as function of track slip (see Equation 3). The BWM was used to evaluate track performance on MMS and MS materials. Results for F_z = 125 N and F_z = 190 N are presented in Figure 8. The BWM predictions are significantly larger than the measured data for both the MMS and the MS. The rather poor behaviour of the model is due to three factors. First, the model assumes uniform ground pressure distribution and therefore it does not include shear re-setting effects which reduce thrust.

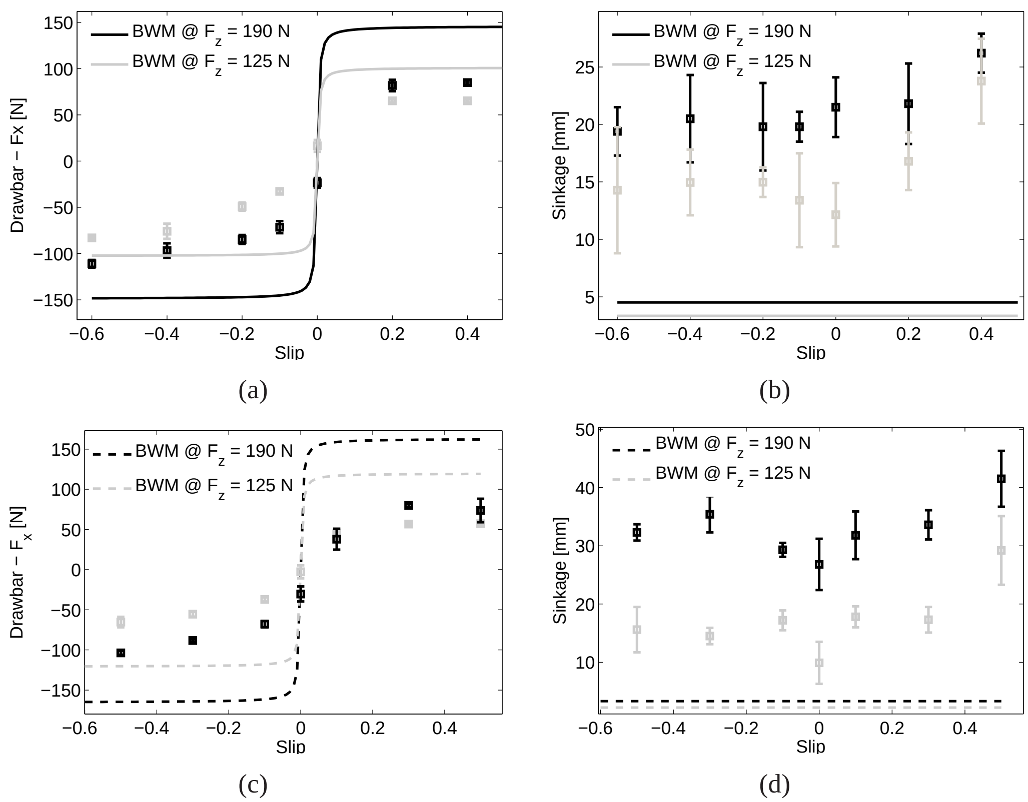


Figure 8: Drawbar and sinkage predictions for the MMS (a and b) and MS (c and d) materials using the basic Wong model (BWM) approach. The BWM largely over estimates drawbar force. This is primarily because sinkage predictions are underestimated and thus compaction resistance is very small.

Second, the shear modulus *k* used for the simulations is small, and this makes the curves steep across zero slip. Third, the calculated sinkage is low, and is not affected by slip (see Equation 3), which reduces the compaction resistance term (see Equation 5) and therefore induces over estimation of drawbar. As previously noted, the BWM does not predict slip-sinkage effects, and therefore the sinkage response is flat as highlighted in Figures 8(b) and 8(d).

Wong has also proposed a more advanced model (AWM) that takes into account the track deflection, shear re-setting effects, and multi-pass effect of the roadwheels [16]. AWM assumes that a track element behaves as a flexible belt and

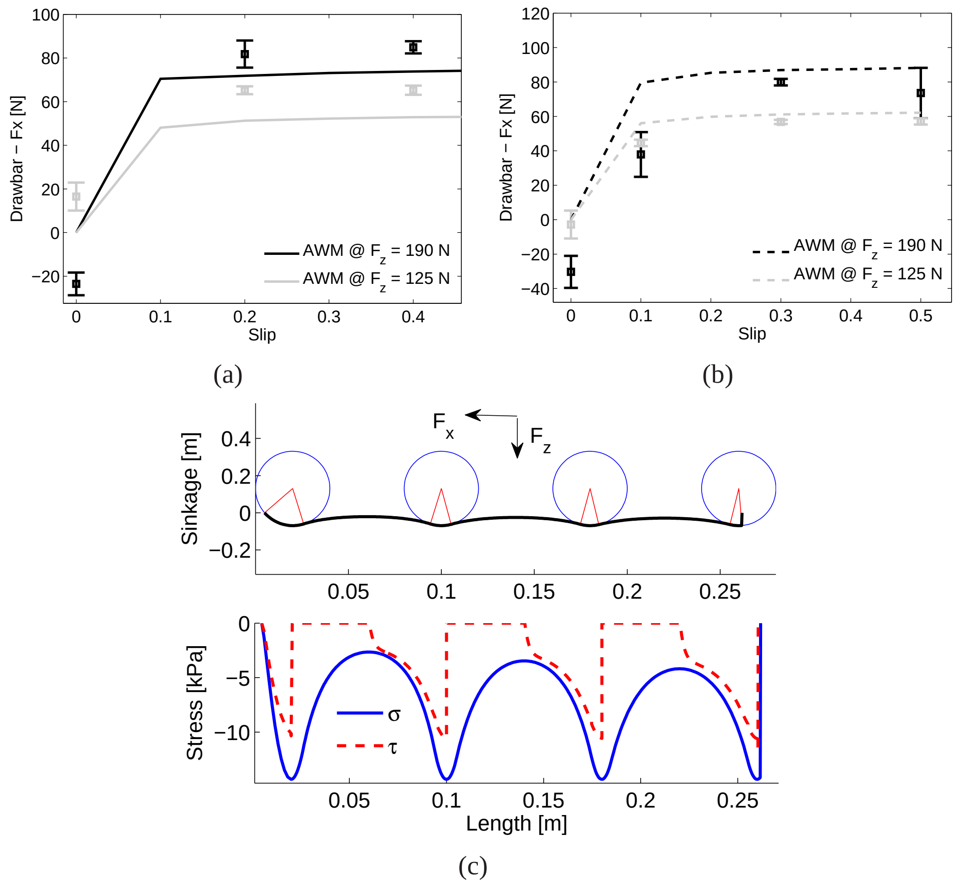


Figure 9: Drawbar predictions for the MMS (a) and the MS (b) materials using the advanced Wong model (AWM) approach. The AWM produces results that are closer to the measured data. (c) shows the belt profile and stress distributions under the roadwheels as calculated by the AWM for the MMS material (results for the MS are very similar). Shear stress profile is influenced by the loading cycles of the normal stress caused by the roadwheels action.

calculates belt deflection between roadwheels by assuming that terrain response is governed by Bekker pressure-sinkage [1] and Janosi-Hanamoto [6] shear-deformation relationships. For more details about the AWM, the reader can refer to [16]. Unfortunately also the AWM does not predict sinkage as function of slip. Therefore, only predictions of drawbar are presented (the analysis is limited to positive slip for the AWM).

Figures 9(a) and 9(b) show AWM predictions for the MMS and the MS at F_z = 125 N and F_z = 190 N. The AWM predictions remain only somewhat accurate, however they are closer to the measured data. Predicted sinkage is in the order of 6-7 mm, and therefore is still under estimated. However, since the AWM includes shear re-setting effects (see Figure 9(c)), the predicted drawbar force is reduced when compared to the BWM. Although pressure-sinkage parameters for the MMS and the MS are considerably different, the performance of the track on the two materials is very similar, strengthening the hypothesis that motion is primarily influenced by terrain frictional characteristics. However, it should be noted that both the AWM and the BWM demonstrated to be sensitive to pressure-sinkage parameters.

4. Conclusions

This paper presented an experimental study of the performance of a single track device on dry, granular soils. The experiments highlighted that track performances are mildly sensitive to the three granular materials under investigation. These materials had very different grain size distribution but similar angle of internal friction indicating that traction is mostly dependent on material's friction. This agrees with terramechanics theories.

Semi-empirical models developed by Wong primarily for large, heavy vehicles were compared to experimental results. BWM showed to be inappropriate for detailed analysis, while the AWM produced better predictions of track performance. Both models showed to be sensitive to pressure-sinkage parameters while the experiments showed that track performances are not influenced by pressure-sinkage behaviour. Further studies will be devolved to extend these results (i.e., model vs. experiment comparisons) to the GV material and to provide a more comprehensive analysis of semi-empirical model performance.

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